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Preliminary palaeomagnetic stratigraphy of the Tertiary Yemen Volcanics

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RESUMEN

Los estudios paleomagnéticos en muestras de 60 sitios en la rocas volcánicas de Yemen (principalmente basaltos) muestran grados altos de dispersión angular entre sitios. Sin embargo, es posible estimar las polaridades normal, reversa e intermedia por medio de desmagnetización térmica. La correlación de los datos de polaridad con la escala de referencia (cróns) puede estimarse de los datos de Ar/Ar, ya que los datos estratigráficos disponibles no permiten una correlación directa. Los basaltos de Yemen parecen haberse formado durante el crón C11r.1r (~29 Ma) y la actividad continua durante unos 3 ó 4 Ma finalizando en el crón C8 (~26 Ma). No obstante que esta interpretación requiere de más datos y sustento, el estudio ilustra el potencial de combinar métodos paleomagnéticos y radiométricos.

PALABRAS CLAVE: Paleomagnetismo, fechamiento Ar/Ar, estratigrafía volcánica, Terciario, secuencia volcánica de Yemen.

ABSTRACT

Mainly basaltic samples from 60 sites in the Yemen Volcanic Group show somewhat high degrees of between-site directional scatter, but enable normal, reversed and intermediate polarities to be identified during thermal demagnetisation. Individual chrons cannot be assigned directly from the available stratigraphic controls, but can be estimated using published $^{39}Ar/^{40}Ar$ determinations. The Yemen plateau basalts appear to have begun eruption during chron C11r.1r , some 29 Ma ago, and eruption persisted for some 3 to 4 Myr, probably terminating during chron C8, some 26 Ma ago. While such an initial assessment needs further substantiation, it demonstrates that the combination of radiometric and palaeomagnetic methods provides far greater reliability than either individual technique alone.

KEY WORDS: Palaeomagnetism, Ar/Ar dating, volcanic stratigraphy, Tertiary, Yemen volcanics.

INTRODUCTION, GEOLOGY AND SAMPLING

The Yemen area is predominantly formed by a PreCambrian-Early Palaeozoic gneissic basement which has been extensively intruded, metamorphosed and folded (Geukens, 1966; Abu KHadra, 1982; El-Anbaawy, 1985). At the end of the Mesozoic, tectonic uplift, with associated erosion, removed most of the Jurassic and Cretaceous sediments from Central Yemen. These movements were accompanied by intense volcanic and intrusive activity that extended throughout most of the Cenozoic of which the dominant sequence is the Yemen Volcanic Group (TKY) which still covers some 5000 km^2 and has a maximum thickness of 3000 m (Menzies *et al*., 1992). The term Yemen Volcanic Group replaces the former name, Trap Series, as recommended by Geukens, (1966). Subsequent to the mainly Palaeocene TKY eruptions, volcanic activity appears to have waned during the Oligocene and Miocene during which time some volcanics became intercalated with freshwater deposits (Grolier and Overstreet, 1983), and some Yemeni volcanic activity appears to have continued into historic times. Palaeomagnetic studies of Miocene volcanic sequences in Syria were reported earlier (Abou-Deeb *et al*., 1999). The most recent radiometric age determinations (Baker *et al*., 1996) suggest that the Yemen Volcanic Group sequences were erupted during 4.4 Ma, between c.31 and 26.5 Ma although older data show a much wider age span. The Series includes bedded alkali flows and pyroclastic rocks including rhyolite, comendite, pantellerite, trachyte, andesite, basalt and ankermite (Shukri and Basta, 1955). These have been divided into six mainly stratigraphic units. However, many of the units have been mapped on their air-photograph characteristics, so the age and stratigraphical relationships of the vast majority of exposures remain problematic. From top to bottom, these units comprise:

TKY6 dark basaltic flows
TKY5 generally leucocratic felsic tuffs with some basaltic flows associated with the formation and collapse of circular volcanic structures.
TKY4 predominantly felsic and tuffaceous , with some basaltic flows, underlies sub-units TKY6 and TKY5.

TKY3 predominantly felsic and tuffaceous; older than TKY4.
TKY2 predominantly felsic and tuffaceous, older than TKY3.
TKY1 predominantly basaltic , but includes green felsic conglomerate, porphyritic trachyte and pink tuffs and overlies the Tawilah Group sediments, the age of which is disputed but contains undisputed Cretaceous and Palaeocene sandstones (Al-Nakhal, 1988, 1990).

During 1991 - 1992 sampling was undertaken within the Yemen Volcanic Group (Figure 1), using field drills and orientation by sun compass, mostly in the vicinity of Sana'a (S sites) and along three major roads from Sana'a east towards Ma'rib (M sites), west towards Hudaydah (H sites) and south towards Ta'izz (T sites). More precise locations are given in the Appendix. Four of the six sub-units of the Yemen Volcanics were sampled; 12 of the 60 sites were in undifferentiated TKY basalts of uncertain stratigraphic position (Table 1). All sites were in flows, with the exception of H15-17 and M4-6, which were in dykes, and sites H5-7 which were in a felsic rock thought to be a dyke. The flows were entirely of basalt, with the exceptions of H13-14 (agglomerates), H15-17 (basic porphyrite), H21-23 and T3 (welded tuffs), and T4-6 (rhyolite).

MEASUREMENT AND ANALYSIS

All samples were sliced to provide one standard palaeomagnetic cylinder, 2.5 cm in diameter, 2.1 cm high, from each drill core. Following the measurement of their initial magnetisation, using a Molspin spinner magnetometer with a noise level of 0.25 mA/m, six samples from different sites were subjected to partial demagnetisation in incremental alternating fields up to 100 mT. Principal component and visual (Kirschvink, 1980) and other analyses did not allow successful separation of meaningful components of remanence. Twelve samples, each from a different site, were subjected to incremental thermal demagnetisation (Table 1) in 9 steps (50, 100, 200, 300, 400, 450, 500, 550, and 600°C) (Figure 2). The low-field susceptibility of these samples was also measured after each temperature increment to monitor thermo-chemical changes in the magnetic mineralogy. The initial intensities of remanence were often high (e.g. S9.1 10.79 A/m, T1.3 9.1 A/m, M3.6 8.2 A/m and H17.4 6.9 A/m) and generally showed only a slight decrease after heating to 200° to 300°C, and some showing slight increases in intensity. The low-field susceptibilities remained essentially constant up to at least 300°C but above 350° to >450°C, changes in both intensity and susceptibility commonly occurred, signifying thermally induced chemical changes in the magnetic mineralogy. A linear component could usually be defined (Kirschvink, 1980) between 100° and 350°-450°C which was considered to be the characteristic direction of magnetisation of the rocks. Half of the linearities had an associated mean diagonal angle, mda, exceeding 5° and were therefore considered to be only moderately well defined. The directional consistency index (Tarling and Symons, 1967) was generally greater than 2, suggesting good consistency in direction, but these were often established between 20° and 100°C, indicating that the low thermal blocking temperature component was more consistent in direction than that of the high blocking temperature component. On the basis of these studies, all remaining samples were thermally demagnetised between 200° and 300°C and their corresponding directional consistency and linearity parameters were determined over this range. The site mean characteristic directions were calculated using only sample linear directions with an mda < 5° and a directional consistency > 2 (Table 2). While both consistency and linearity analyses indicate that one third of the site mean directions are well defined, α_{95} < 10°, the other two thirds are less precise, although considered to be adequately defined for magnetostratigraphic evaluation. As these volcanics are relatively young, Palaeocene in age, their site polarity has been assigned on the latitude of the mean site virtual geomagnetic pole (VGP), i.e. normal (N) for a northerly VGP latitude > 30°N and reversed (R) for a southerly VGP latitude > 30°S. Intermediate polarities (I) are defined as site VGP latitudes < 30°N/S. Sites with VGP latitudes between 30° and 50° N/S are identified as Ni and Ri respectively.

RESULTS

The stratigraphically youngest sites (T4, T5 and T6) were all from the same rhyolite in unit TKY5, of which site T4 was too scattered to define a mean direction. The other site mean directions were moderately well defined. One was of normal polarity and the other intermediate (Table 2, Figure 3a). Only one of the 13 TKY4 sites was too scattered to estimate a mean site direction; the remaining 12 site directions were mostly defined by an α_{95} precision estimate of < 20° and comprised 4 normal, 5 reversed and 3 intermediate polarities. Despite the site mean precision estimates, the between-site directional scatter was large (Table 2, Figure 3b), even for sites thought to have been from the same dyke-like basalt (H8-H12). There was a regional grouping of the TKY4 polarities. All of the sites from road sections along the Hudaydah road were reversed or intermediate, apart from site H8, while those from around Sana'a were of normal or intermediate polarity. All 11 TKY2 sites were from along the Ta'izz road and were defined with α_{95} precision estimates < 25°; mostly < 12°. Two sites were of intermediate polarity, 4 were normal and 5 of reversed polarity (Table 2, Figure 3c). Nine of the 21 TKY1 sites directions were defined with a precision estimate, α_{95} < 10°, but 4 sites were too scattered to define a mean direction (Table 2, Figure 3d). Fifteen of the remaining site mean directions were of normal polarity, with two of intermediate polarity and no reversed polarities. Six of the undifferentiated TKY sites had well defined site mean precisions, α_{95} < 10°; one site direction was not definable (Table 2, Figure 3e). All of the sites from near Sana'a,

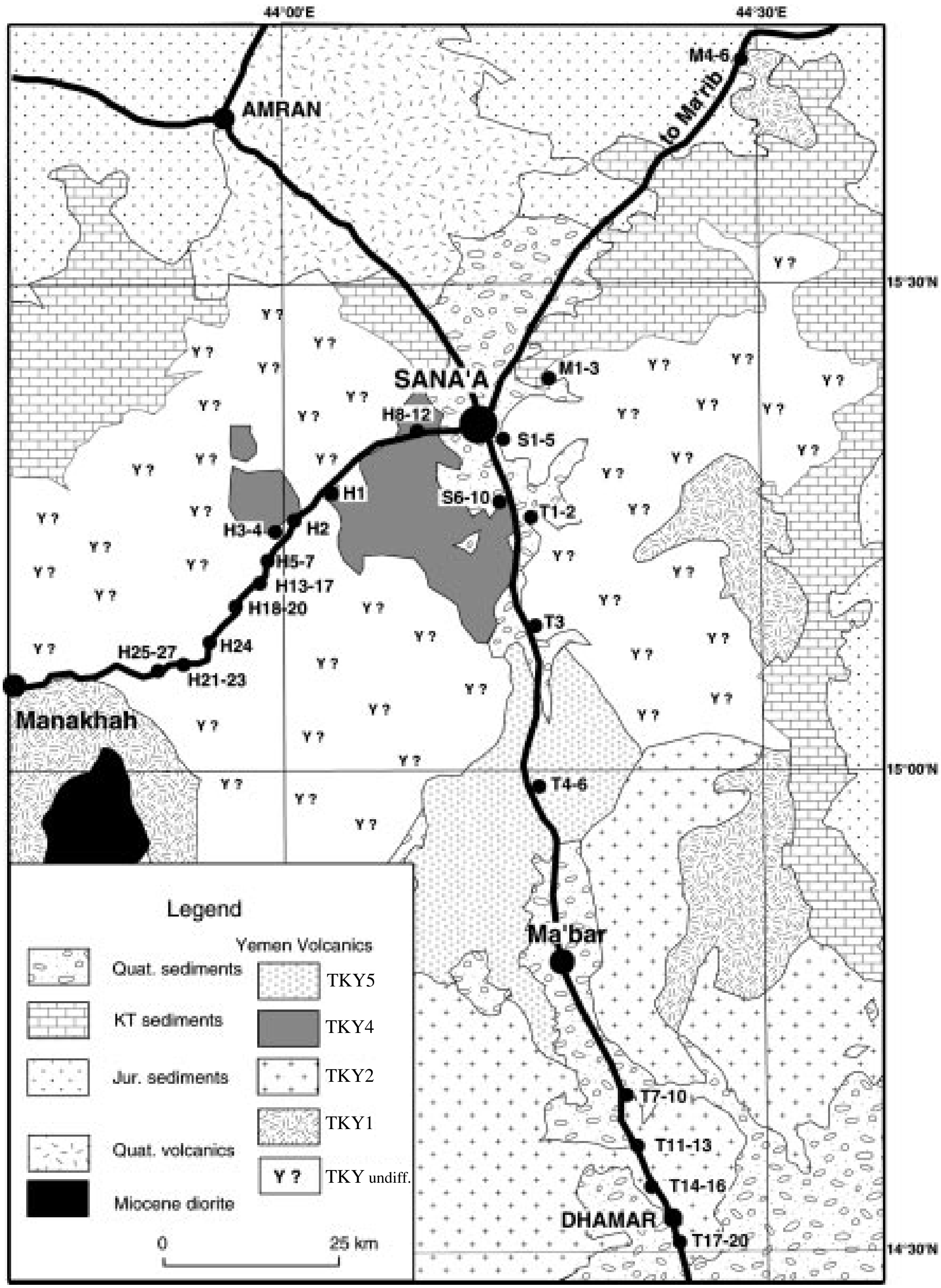

Fig. 1. Location of sampling sites in the Yemen Volcanic Series. S = Sana'a sites; T = Sana'a - Ta'izz road; M = Sana'a - Ma'rib road; H = Sana'a - Hudaydah road. Note that the "undifferentiated Yemen Volcanics (Y ?) along the Sana'a-Manakhah road include several areas, such as those where sites H5-7 and H13-27 were sampled, that are known to correspond to TKY1. However, the boundaries are indistinct and impractical to illustrate on the scale of this simplified illustration.

Table 1

Pilot Sample Consistency and Linearity Characteristics

Sample	*CI*	*range*	*Decl*	*Incl*	*mda*	*range*	*Decl*	*Incl*	*Pol*
TKY5									
T 4.1	2.7	100-300	17.4	18.0	5.0	100-450	22.1	18.8	N
TKY4									
H 1.1	1.7	20-100	289.2	-10.1	0.6	500-zero	318.9	17.5	N
S 6.3	4.9	20-200	55.5	9.1	4.8	20-400	56.4	7.1	N
TKY2									
H 14.6	5.6	200-500	55.3	34.7	5.1	100-400	49.3	57.3	N
T 7.1	18.4	200-400	191.7	-40.4	2.7	300-450	182.0	-40.6	R
T19.1	3.1	20-200	20.8	15.2	7.1	100-300	23.7	19.2	N
TKY1									
H 7.6	2.0	20-100	5.4	-0.2	6.4	50-200	12.8	-1.7	I
H23.2	2.4	20-400	19.7	13.7	4.8	50-300	354.1	6.7	N
M 4.3	3.3	50-450	12.3	-12.7	4.4	400-500	348.2	16.9	N
TKY (undifferentiated)									
M 1.1	1.9	20-100	206.8	-27.5	7.8	400-500	230.4	70.5	R
S 1.2	3.0	100-300	182.7	-7.1	6.3	100-300	1.8	-62.0	R
T 1.2	3.9	20-100	59.8	32.8	8.3	20-zero	59.8	33.8	N

CI is the Consistency Index (formerly the Stability Index) of Tarling and Symons (1967), N is the total number of samples. *mda* is the mean diagonal angle defining the linearity of the vector (Kirschvink 1980). Range is the treatment range over which the directions are consistent or linear. The polarity, Pol., is defined as N for sites where the virtual geomagnetic pole (VGP) has a latitude >30°N, R = <30°S, I = 30°N < VGP latitude>30°S.

including the three Ma'rib road exposures, were of reversed polarity while the two sites from the Ta'izz road were of normal polarity, and the one site from the Hudaydah road was of intermediate polarity.

INTERPRETATION AND ASSESSMENT

The palaeomagnetic data shows more between-site scatter than would be expected for the precision of most of the individual mean site directions but is unlikely to be due to differential tectonic tilts as identified tilts are far smaller than the observed between-site dispersion. Thermo-chemical changes mostly occur above 350°-450°C, but may account for some of the dispersion, as may the presence of unidentified components associated with localised lightning effects. While such components inhibit any assessment of the magnitude of palaeo-secular variations, they are unlikely to be of sufficient magnitude to affect an assessment of polarity. However, such scatter does not allow palaeosecular variation properties to be used to identify individual polarity chrons. However, the few sites involved do not allow realistic estimation of the magnitude of secular variation for any of the volcanic units. This also means that it is not possible to characterise particular polarity chrons by variation in their detailed polarity structure, as suggested by Hailwood (1997). Uncertainties in the mapped stratigraphy also inhibits the establishment of regional stratigraphic polarity sequences. However, it is possible to attempt an assessment of possible polarity chrons on the basis of the number of sites of either polarity in each volcanic unit. For example, if all sites from a given stratigraphic unit are of the same polarity, then these are more likely to represent a longer chron than a similar sequence of mixed polarities. Where such a sequence can be dated radiometrically, it should be possible to use available radiometric ages, together with the known stratigraphic relationships between sites, to assess the mostly likely correlations between the assigned radiometric ages, the observed polarities and the relevant chrons within the Geomagnetic Polarity Time Scale (Table 4).

The radiometric ages for the Yemen Volcanic Group (Capaldi *et al.*, 1983, 1987a,b,c; Civette *et al.*, 1978; Chiesa *et al.*, 1989; Menzies *et al.*, 1992; Manetti *et al.*, 1991; Huchon *et al.*, 1991; Al-Kadasi , 1994; Baker *et al.* 1996) extend over

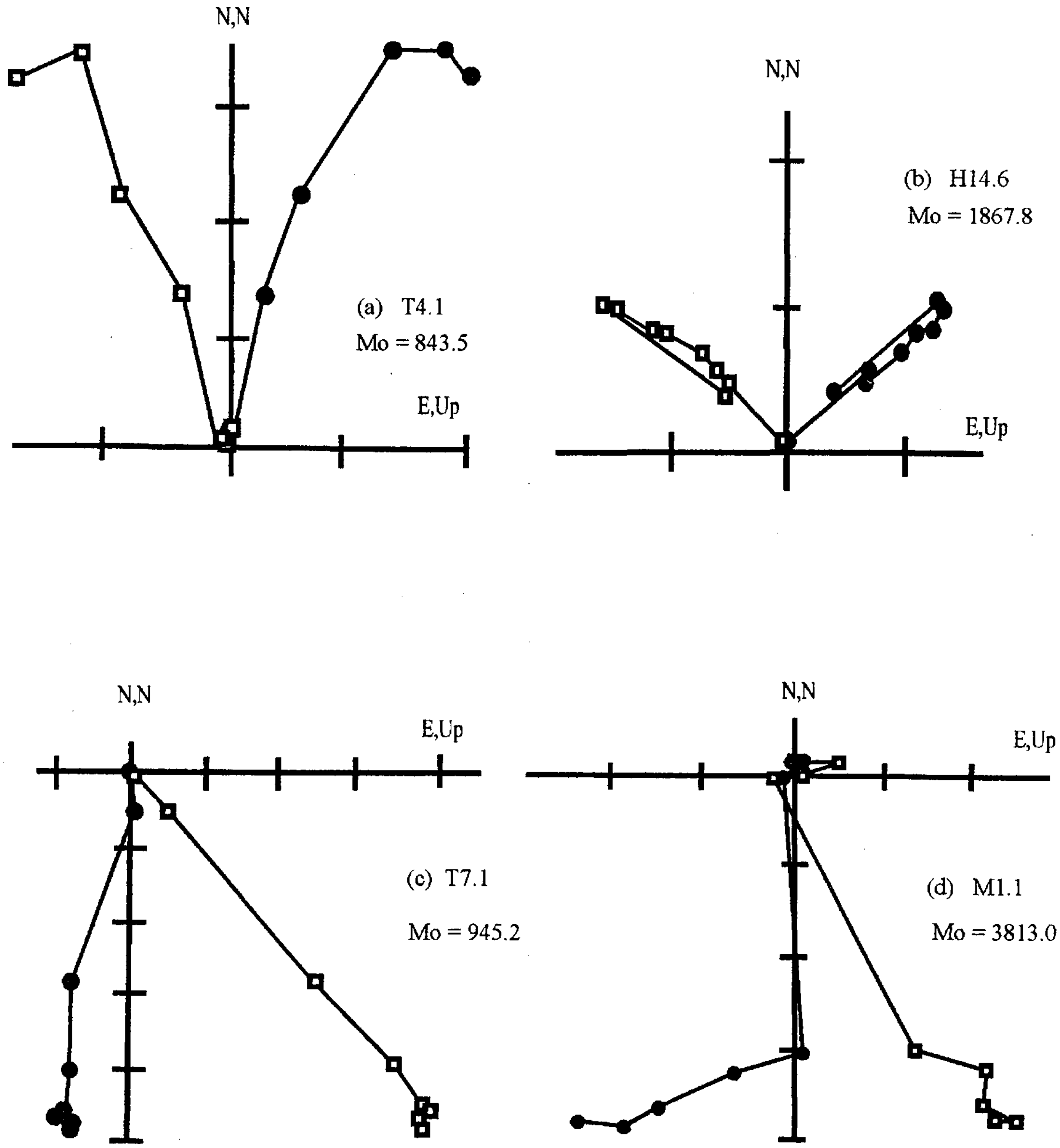

Fig. 2. Examples of thermal demagnetisation. The Cartesian projections show the horizontal components (N,E) with solid dots, and the vertical components (N,Up) as hollow squares. Mo is the initial intensity of remanence in mA/m. The heating steps were 20, 50, 100, 200, 300, 400, 450, 500, 550 and 600°C. (a) Sample T4.1 is the TKY5 series; (b) H14.6 and (c) T7.1 from the TKY2 series and (d) sample M1.1 from the undifferentiated TKY from TKY1 series.

more than 50 Myr. Baker *et al.* (1996) considered that much of this range was due to the problems (mostly argon loss) arising from whole rock K/Ar determinations and, on the basis of their $^{39}Ar/^{40}Ar$ determinations, they concluded that the actual time-span represented was short, with eruptions commencing in different areas between 30.9 and 29.2 Ma, and ceasing at only slightly different times, 26.9 to 26.5 Ma, in different areas. As both Baker *et al.* (1996) and Huchon *et al.* (1991) both reported the latitudes and longitudes of their sampling sites, it has been possible to evaluate the probable age of several of the palaeomagnetic sites collected in 1991, before the radiometric determinations were available. Thus we may incorporate magnetic polarity considerations into an assessment of the age and stratigraphy of the Yemen Volcanics.

The samples from oldest Yemen Volcanics, TKY1, which immediately overlie the Palaeocene Tawilah Group sediments, came from two separate regions: the Hudaydah and Ma'rib roads. These are all of normal or intermediate polarity (Table 2). Radiometric ages, using only K/Ar, are available for sites H5 and H6 along the Hudaydah road,

Table 2

Site Mean Directions, Polarity and Radiometric Ages

			Characteristic		**Virtual Pole**				
Site	**N**	**Decl.**	**Incl.**	***k***	α_{95}	**Lat.**	**Long.**	**Pol.**	**Radiometric Age**
TKY5									
T 4	5		highly scattered (α_{95} >30°)						(19.2 - 23.6)[1]
T 5	5	7.6	48.8	34.1	13.3	73.7	68.4	N	(19.2 - 23.6)[1]
T 6	6	67.9	58.2	10.4	21.7	26.4	98.0	I	(19.2 - 23.6)[1]
TKY4									
S 6	6	44.8	14.3	73.9	7.8	45.4	139.4	Ni	
S 7	6	14.4	7.0	152.6	5.4	71.6	172.5	N	
S 8	6		highly scattered (α_{95} >30°)						
S 9	5	6.9	-9.9	19.9	15.4	68.6	205.1	N	
S10	5	71.0	30.8	31.1	13.9	22.1	122.2	I	
H 1	6	240.0	6.4	6.3	28.9	-27.8	310.9	I	
H 3	6	214.0	-26.2	34.0	11.7	-57.1	311.9	R	26.9-27.8[2]
H 4	5	289.0	6.2	14.2	21.0	19.0	312.0	I	26.9-27.8[2]
H 8	5	324.8	-50.9	274.7	4.6	32.1	259.6	Ni	28.9±0.2[2]
H 9	6	135.0	-23.2	89.1	7.1	-46.2	135.7	Ri	
H10	5	153.0	4.7	80.0	8.6	-57.9	102.9	R	
H11	5	193.5	31.0	29.5	14.3	-55.2	21.1	R	
H12	5	233.3	10.0	26.1	15.2	-33.4	331.1	Ri	
TKY2									
T 7	5	23.8	37.8	13.5	21.6	66.5	114.8	N	(22.3±0.7)[1]
T10	4	65.1	29.0	78.4	10.4	27.4	124.2	I	(22.3±0.7)[1]
T11	4	229.6	21.1	18.3	22.0	-34.6	339.1	Ri	
T12	6	21.2	6.1	58.3	8.8	66.1	161.3	N	
T13	6	231.9	1.7	37.8	11.0	-36.4	326.6	Ri	
T14	6	177.7	37.0	126.7	6.0	-54.7	48.1	R	
T15	6	227.6	-31.8	46.5	9.9	-44.3	304.4	Ri	
T16	6	182.2	-41.6	313.6	3.8	-80.4	236.6	R	
T17	4	117.2	50.3	12.7	26.9	-14.5	96.3	I	
T18	5	1.2	13.1	56.5	10.3	82.0	215.8	N	
T19	4	357.7	38.8	53.1	12.7	82.3	28.3	N	
TKY1									
H 5*	5	314.0	18.3	22.2	16.6	44.8	312.1	Ni	23.3±0.4[1]
H 6*	5	322.7	22.9	17.2	19.0	53.6	313.5	N	23.3±0.4[1]
H 7*	5	9.2	11.6	17.9	18.6	77.0	178.9	N	
H13	6	28.4	3.9	350.1	3.6	59.1	156.3	N	
H14	6	49.5	31.4	78.7	7.6	42.5	124.5	Ni	
H15*	6	280.3	16.5	138.0	5.7	12.1	319.5	I	
H16*	4	348.2	23.6	46.1	13.7	78.2	301.7	N	
H17*	6	302.2	5.9	66.6	8.3	31.8	307.9	Ni	
H18	6		highly scattered (α_{95} >30°)						
H19	6		highly scattered (α_{95} >30°)						

H20	5	132.1	32.8	8.2	28.4	-32.4	100.7	Ni	
H21	4	15.3	5.0	21.4	20.3	70.3	172.7	N	
H22	6	8.2	7.8	224.5	4.5	76.2	187.3	N	
H23	6	22.1	17.5	15.7	17.5	67.5	147.2	N	
H24	5	345.7	4.0	97.8	7.8	70.8	272.4	N	
H25	6		highly scattered (α_{95} >30°)						
H26	6	71.8	-27.2	49.9	9.6	13.0	153.3	I	
H27	6		highly scattered (α_{95} >30°)						
M 4*	6	28.2	-6.7	34.8	13.2	56.3	166.4	N	
M 5*	4	1.3	22.4	145.0	7.7	85.8	206.6	N	
M 6*	6	35.3	-11.8	58.5	8.8	48.9	163.5	Ni	
TKY (undifferentiated)									
S 1	4	164.8	-13.1	23.7	19.3	-72.7	105.4	R	29.65±0.64[2]
S 2	7	177.4	-5.6	578.5	2.8	-77.1	56.0	R	29.85±0.18[2]
S 3	7	194.2	-1.0	677.5	2.6	-69.5	359.6	R	
S 4	6	183.5	-2.5	39.4	9.7	-75.4	30.2	R	
S 5	6	160.2	-6.7	122.6	5.5	-67.1	104.5	R	
M 1	4	184.3	-16.8	83.4	10.1	-82.0	12.1	R	(29.23±0.28)[2]
M 2	4	155.1	-1.7	31.6	16.6	-61.4	106.0	R	
M 3	6	172.1	-5.8	35.8	11.4	-75.3	77.0	R	
H 2	6	124.8	54.7	302.2	3.9	-17.4	88.2	I	
T 1	6	23.3	47.1	9.6	22.7	64.8	99.3	N	
T 2	6	323.5	2.5	164.4	5.2	51.3	296.5	N	28.2-29.3[2]
T 3	6		highly scattered (α_{95} >30°)						28.2-29.3[2]

Intrusives are marked by an asterisk (*). N is the number of samples used, with their precision estimates, *k* and α_{95}, as defined by Fisher (1953). The polarities, Pol., are N, R and I as defined for Table 1, with subscript i for normal sites or reversed sites with VGP palaeolatitudes between 30 and 50°N/S. The radiometric ages are[1] based on whole rock K/Ar analyses (Huchon *et al*., 1991), or[2] whole-rock analyses using $^{39}Ar/^{40}Ar$ (Baker *et al*., 1996). The radiometric ages were determined on samples estimated to have been taken within 5 km of the palaeomagnetic sampling site except those in parentheses which, although more distant localities, are still considered to correlate with the palaeomagnetic sampling area. The range is given where more than one radiometric age determination is available from the same locality.

23.3±0.4 Ma (Huchon *et al*., 1991). This age, taken at face value, would correspond to chron C6Cn.1n (23.357 to 23.537 Ma; Cande and Kent, 1992) which was relatively short (180 kyr). However, doubts have been expressed about such whole-rock K/Ar dates (Baker *et al*., 1996). Normal polarity rocks, from the undifferentiated TKY, have much older $^{39}Ar/^{40}Ar$ ages of 28.2 to 29.3 Ma. Assuming that sites T2 and T3 can be assigned to TKY1, their age would suggest that their polarities were acquired during normal polarity chrons C10n.1n (28.255 to 28.484 Ma) and/or C10n.2n (28.550 to 28.716 Ma) with durations of 0.229 and 0.166 Myr respectively (Cande and Kent, 1992). However, other undifferentiated TKY lavas have older $^{39}Ar/^{40}Ar$ ages and are of reversed polarity. If these radiometric ages are accepted, then the observed polarity corresponds to the relatively long (0.657 Myr) C11r.1r reversed chron (29.737 - 29.633 Ma - Cande and Kent, 1992). This suggests that the onset of the Yemeni volcanism was during chron C11r.1r , some 29 Ma ago, and that the first Yemen Volcanic unit persisted through the normal C10n chrons following. This also implies that the K/Ar radiometric ages corresponding to H5-6 have suffered some 12% argon loss equivalent to some 4 Myr in radiometric age.

The TKY2 lavas, sites T7-T10, have a K/Ar radiometric age of 22.3±0.7 Ma (Huchon *et al*., 1991) but underlie TKY4 lavas with older $^{39}Ar/^{40}Ar$ age determinations of 26.9 to 29.1 Ma (Baker *et al*., 1996), again suggesting possible argon loss equivalent to some 4 Ma from sites T7-10. The lavas of this Yemen Volcanic unit are of both normal and reversed polarity and the imprecision in the radiometric age means that the normal polarities might correlate with normal chrons in C10 (C10n.1n; 28.255 to 28.484 Ma and C10n.2n; 28.550 to 28.716 Ma - Cande and Kent, 1990). However, this assessment must also be considered with that of the stratigraphically younger TKY4 unit which includes $^{39}Ar/^{40}Ar$ radiometric ages of 26.9 to 29.1 Ma (Baker *et al.,* 1996) for lavas of both normal and reversed polarity and thus correlates with chrons C9 and C10 (29.37 to 27.00 Ma). If TKY2 ages are correctly assigned to younger units, then unit TKY4 would be expected to be more related to chron C10,

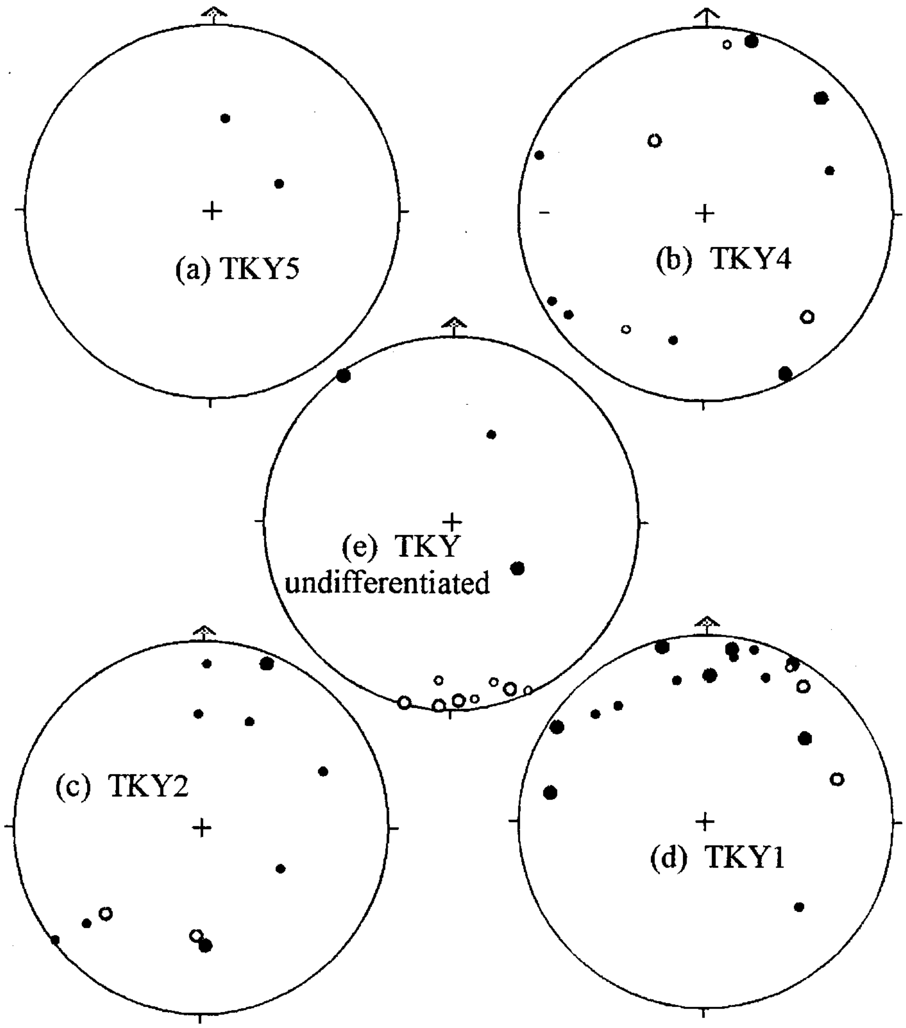

Fig. 3. The site mean directions. (a), (b), (c), (d) and (e) are repectively site mean directions for the TKY5, TKY4, TKY2, TKY1 and TKY undifferentiated volcanic units. The projections are equal area, with vertical inclinations plotting at the centre. Positive (downward) inclinations are shown with solid dots and negative (upward) inclinations with hollow circles. The more precisely defined site mean directions, $\alpha_{95} <$ 10°, are twice the size of less well defined site directions. Site mean directions with precision estimates $\alpha_{95} >$ 30° are considered undefined.

while TKY2 would correlate with chron C9. However, these two units, together with TKY3 (not sampled), appear to be virtually coeval as they occur within the currently available precision in the stratigraphic, radiometric and magnetic determinations. The youngest unit, TKY5, comprises one normal and one intermediate site, with K/Ar age determinations between 19.2 and 23.6 Ma (Huchon *et al.*, 1991). If a similar argon loss is postulated, then their radiometric age would be consistent with chron C8n.2n.

CONCLUSIONS

While the site directions of remanence found in this study have relatively low precision when compared with most studies of other Tertiary plateau basalts, for example from the Palaeocene British Tertiary Igneous Province (e.g. Tarling, 1970; Mussett *et al.* 1980), they appear to have sufficient precision to enable the initial polarity to be determined for the time of the eruption of most of the Yemen Volcanic Group, although no estimate can be made of the magnitude of geomagnetic secular variations. However, the rapid rate of polarity changes during the Palaeocene (Table 4), combined with the few number of sites in each unit and the high directional scatter, does not enable specific polarity chrons to be uniquely identified on the geomagnetic characteristics of any individual chron. If the radiometric ages for the Yemeni Volcanics, based on K/Ar determinations (Huchon *et al.*, 1991), are assumed to have suffered argon loss, as speculated by Baker *et al.* (1996), and that this argon loss corresponds to an increase in their radiometric age by some 4 Myr, it is possible to use both the K/Ar and $^{39}Ar/^{40}Ar$ dates to evaluate the most probable chrons represented by the polarities of the palaeomagnetic sites. Such assumptions suggest that the

Table 3

The Site Polarities for Different Yemen Volcanic Units

TKY Unit	Sites	N	R	I	Scattered
5	3	1	0	1	1
4	13	4	5	3	1
2	11	4	5	2	0
1	21	15	0	2	4
Undiff.	12	2	8	1	1
TOTAL	60	26	18	8	7

The normal (N), reversed (R) and intermediate (I) polarities are defined in Table 1. Undiff. = TKY undifferentiated.

Table 4

Normal polarity chrons and their duration which occurred during the possible eruption of the Yemen Volcanics based on radiometric determinations

Normal Chron	Age (Ma) Start	End	Duration (Myr)
C6Bn.1n	22.599	22.760	0.161
C6Bn.2n	22.814	23.076	0.262
C6Cn.1n	23.357	23.537	0.180
C6Cn.2n	23.678	23.800	0.122
C6Cn.3n	23.997	24.115	0.118
C7n.1n	24.722	24.772	0.050
C7n.2n	24.826	25.171	0.345
C7An	25.482	25.633	0.151
C8n.1n	25.807	25.934	0.127
C8n.2n	25.974	26.533	0.559
C9n	27.004	27.946	0.942
C10n.1n	28.255	28.484	0.229
C10n.2n	28.550	28.716	0.166
C11n.1n	29.373	29.633	0.260
C11n.2n	29.737	30.071	0.334
C12n	30.452	30.915	0.463

Polarity chron durations after Cande and Kent (1992).

onset of the Yemen Volcanics occurred during chron C11r.1r, some 29 Ma ago, and that eruption persisted for some 3 to 4 Myr, probably terminating during chron C8, some 26 Ma ago. However, it must be emphasised that this assessment relies heavily on the reliability of the available $^{39}Ar/^{40}Ar$ determinations and further radiometric and palaeomagnetic analyses are required to establish the veracity of these conclusions.

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APPENDIX

All sites are basaltic, unless otherwise stated.

Site	*Lat.(N)*	*Long.(E)*	*Location*
H 1	15 18 00	44 04 00	500 m before Mend village, 15 km from Sana'a
H 2	15 14 00	44 01 00	3 km from Matna, 21.5 km from Sana'a
H 3	15 14 00	44 01 00	500 m from H2; strat below H2 and separated by lateritic soil 20 m thick
H 4	15 14 00	44 01 00	25m from H3 and same flow
H 5	15 09 40	43 57 00	dyke-like basalt in felsic rock, Jabal Al Manar, 1 km before Al Khamis
H 6	15 09 40	43 57 00	same as H5
H 7	15 09 40	43 57 00	same as H5
H 8	15 21 00	44 09 00	Jabal Asr, 500 m on right from road
H 9	15 21 00	44 09 00	as H8
H10	15 21 00	44 09 00	as H8
H11	15 21 00	44 09 00	as H8
H12	15 21 00	44 09 00	as H8
H13	15 08 30	43 56 30	agglomerate with pyroclastic rocks
H14	15 08 30	43 56 30	agglomerate with pyroclastic rocks
H15	15 08 30	43 56 30	basic porphyritic dyke
H16	15 08 30	43 56 30	basic porphyritic dyke
H17	15 08 30	43 56 30	basic porphyritic dyke
H18	15 08 00	43 56 00	basalt with porphyritic olivine, 65 km from Sana'a
H19	15 08 00	43 56 00	basalt with porphyritic olivine, 65 km from Sana'a

Site	*Lat.(N)*	*Long.(E)*	*Location*
H20	15 08 00	43 56 00	basalt with porphyritic olivine, 65 km from Sana'a
H21	15 06 30	43 54 30	green welded tuff, 75 km from Sana'a
H22	15 06 30	43 54 30	green welded tuff, 75 km from Sana'a
H23	15 06 30	43 54 30	green welded tuff, 75 km from Sana'a
H24	15 07 00	43 55 30	ignimbrite, 70 km from Sana'a
H25	15 06 30	43 53 00	14 km W of H24
H26	15 06 30	43 53 00	14 km W of H24
H27	15 06 30	43 53 00	14 km W of H24
S 1	15 21 00	44 14 00	quarry on Jabal Naqum E of Sana'a
S 2	15 21 00	44 14 00	quarry on Jabal Naqum E of Sana'a, 100m from S1
S 3	15 21 00	44 14 00	quarry on Jabal Naqum E of Sana'a, 100m from S2
S 4	15 20 00	44 14 00	300 m S of Sana'a
S 5	15 20 00	44 14 00	10 m E of S4
S 6	15 17 00	44 13 30	1 km S of Haziez, nr Al-Nahden mntn
S 7	15 17 00	44 13 30	50 m N of S6, rt side Tai'zz road
S 8	15 17 00	44 13 30	50 m N of S7
S 9	15 17 00	44 13 30	50 m NW of S8
S10	15 17 00	44 13 30	15 m N of S9
T 1	15 15 40	44 15 08	500 m before Daba'a Khyra, 20 km from Sana'a
T 2	15 15 40	44 15 08	50 m before Daba'a Khyra, 20 km from Sana'a
T 3	15 08 22	44 16 00	welded tuff, Blad Al Rous nr Al Saar, 38 km from Sana'a
T 4	15 00 00	44 16 00	rhyolite, 2 km before Jabal Mosleh
T 5	15 00 00	44 16 00	rhyolite, 2 km before Jabal Mosleh
T 6	15 00 00	44 16 00	rhyolite, 2 km before Jabal Mosleh
T 7	14 40 16	44 20 51	13 km S of Ma'bar
T10	14 40 16	44 20 51	13km S of Ma'bar
T11	14 36 12	44 22 17	17 km from Ma'bar
T12	14 36 12	44 22 17	17 km from Ma'bar
T13	14 36 12	44 22 17	17 km from Ma'bar
T14	14 34 15	44 23 42	27 km from Ma'bar
T15	14 34 15	44 23 42	27 km from Ma'bar
T16	14 34 15	44 23 42	27 km from Ma'bar
T17	14 30 00	44 24 51	3 km S of Dhmar towards Yarem
T18	14 30 00	44 24 51	3 km S of Dhmar towards Yarem
T19	14 30 00	44 24 51	3 km S of Dhmar towards Yarem
M 1	15 24 35	44 17 15	quarry nr Ma'rib road nr Sa'awan
M 2	15 24 35	44 17 15	quarry nr Ma'rib road nr Sa'awan
M 3	15 24 35	44 17 15	quarry nr Ma'rib road nr Sa'awan
M 4	15 38 46	44 29 09	7m wide dyke, 7 km from Kholikah
M 5	15 38 46	44 29 09	7m wide dyke, 7 km from Kholikah
M 6	15 38 46	44 29 09	7m wide dyke, 7 km from Kholikah

BIBLIOGRAPHY

ABOU-DEEB, J. M., M. M. OTAKI, D. H. TARLING and A. L. ABDELDAYEM, 1999. A palaeomagnetic study of Syrian volcanic rocks of Miocene to Holocene age. *Geophys. Internac. 38,* 17-26.

ABOU KHADRA, A. M., 1982. Sedimentological evolution of the Yemen Arab Republic. *Bull. Fac. Sci., Sana'a Univ., 2,* 39-55.

AL-KADASI, M. A., 1994. Temporal and spatial evolution of the basal flows of the Yemen Volcanic Group. Ph. D. thesis, University of London.

AL-NAKHAL, H., 1988. Stratigraphy of the Tawilah Formation (Cretaceous-Paleocene) in Yemen Arab Republic. *M.E.R.C., Ain Shams Univ., Earth Sci. Ser., 2,* 161-171.

AL-NAKHAL, H., 1990. Review of the stratigraphy of the Phanerozoic in the Republic of Yemen: (in Arabic). *Dirasat Yamaniyyah*, *42,* 152-199.

BAKER, J. L. SNEE and M. MENZIES, 1996. A brief period of flood volcanism in Yemen: implications for the duration and rate of continental flood volcanism at the Afro-Arabian triple junction. *Earth Planet. Sci. Lett., 138,* 39-55.

CANDE, C. and D. KENT, 1992. A new geomagnetic polarity time scale for the late Cretaceous and Cenozoic. *J. Geophys. Res.*, *97,* 13917-13951.

CAPALDI, G., P. MANETTI and G. B. PICCARDO, 1983. Preliminary investigations on volcanism of the Sadah region (Yemen Arab Republic). *Bull. Volc. 46,* 413-427.

CAPALDI, G., S. CHIESA, P. MANETTI, O. ORSI and G. POLI, 1987a. Tertiary anorogenic granites of the western border of Yemen Plateau. *Lithos 20,* 433-444.

CAPALDI, G., S. CHIESA, S. CONTICELLI and P. MANETTI, 1987b. Jabal al Nar: an upper Miocene volcanic center near al Mukha (Yemen Arab Republic). *J. Volc. Geoth. Res. 31*, 345-351.

CAPALDI, G., P. MANETTI, G. B. PICCARDO and G. POLI, 1987c. Nature and geodynamic significance of the Miocene dyke swarm in North Yemen (YAR). *N. Jahrb. Miner. Abh. 156,* 207-229.

CHIESA, S., L. CIVETTA, M. DEFINO, L. LA VOLPE and O. ORSI, 1989. The Yemen Trap Series: genesis and evolution of a continental flood basalt. *J. Volcanol. Geoth. Res. 36,* 337-350.

CIVETTA, L., L. VOLPE and L. LIRER, 1978. K-Ar ages of the Yemen Plateau. *J. Volcanol. Geoth. Res., 4,* 307-314.

EL-ANBAAWY, M. I., 1985. Geology of Yemen Arab Republic. Geology Dept., Sana'a University, Yemen.

FISHER, R. A., 1953. Dispersion on a sphere. *Proc. Roy. Soc., A217,* 295-305.

GEUKENS, F., 1966. Geology of the Arabian Peninsula, Yemen. U.S. Geol. Surv. Prof. Paper 560B, pp. 23.

GROLIER, M. J. and W. C. OVERSTREET, 1983. Geologic map of the Yemen Arab Republic 1:500 000 Scale. U.S. Geological Survey. Miscellaneous Geological Investigations Series Map I-1143-B.

HAILWOOD, A. E., 1997. *In:* Tarling D. H. New and Better Techniques in Palaeomagnetism. *Astron. and Geophys., 38,* 28-29.

HUCHON, P., F. JESTIN, J. M. CANTAGREL, J. M. GAULIER, S. AL-KHIRBASH and A. GAFANEH, 1991. Extensional deformation in Yemen since Oligocene and the Africa-Arabia-Somalia triple junction. *Annales Tectonicae, 5,* (2) 141- 163.

KIRSCHVINK, J. L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophys. J. R. Astr. Soc., 62,* 699-718.

MANNETTI, P., G. CAPALDI, S. CHIESA, L. CIVETTA, S. CONTICELLI, M. GASPARON, L. LA VOLPE and G. ORSI, 1991. Magmatism of the eastern Red Sea margin in the northern part of Yemen from Oligocene to Recent. *Tectonophysics, 198,* 181-202.

MENZIES, M. A., D. W. J. BOSENCE, H. A. NAKHAL, S. AL-KHIRBASH, M. A. AL-KADASI, K. R. MACLAY, G. J. NICHOLAS and A. K. AL-SUBBARY, 1992. Lithospheric extension and the opening of the Red Sea: sediment-basalt relationship in Yemen. *Terra Nova, 2,* 340-350.

MUSSETT, A. E., P. DAGLEY and R. R. SKELHORN, 1980. Magnetostratigraphy of the Tertiary igneous succession of Mull, Scotland. *J. Geol. Soc. Lond., 137,* 349-357.

SHUKRI, N. M. and E. Z. BASTA, 1955. Petrography of the alkaline rocks of Yemen. *L'Institut d'Egypte Bull., 36,* 129-163.

TARLING, D. H., 1970. Palaeomagnetic results from the Faeroe Islands. *In:* Palaeogeophysics Ed. S.K. Runcorn, Acad. Press, Lond., 193-208.

TARLING, D. H. and D. T. A. SYMONS, 1967. A stability index of remanence in palaeomagnetism. *Geophys. J. R. Astr. Soc., 12,* 443-448.

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